PROSPECTS FOR THE DETECTION OF HIGHER ORDER WEAK PROCESSES AND THE STU OF WEAK INTERACTIONS AT HIGH ENERGY*

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Contents

1. Introduction

The first observation of weak interactions is now over 75 years old.[1] An impressive array of understanding of a vast number of phenomena has been achieved for low energy processes, and yet some of the simplest questions that can be asked about the basic nature of the weak interaction can not presently be answered. In many ways we know less about this interaction than we do about the strong interaction. Apparently Heisenberg was the first to recognize the significance of the dimensionality of the coupling constant of the lowest order current-current interaction.[2] The lowest order interaction being

$$H_{eff} = \frac{G}{\sqrt{2}} j_\lambda j_\lambda^+ \tag{1}$$

where j_λ, j_λ^+ are appropriate currents and G is the coupling constant. G has the dimensions of $(\text{length})^2$ or $(1/m)^2$ with a numerical value

$$G = (1.01 \times 10^{-5})/(m_p)^2$$

In order to form a dimensionless parameter for the weak interaction it is frequently suggested to use s and to form the parameter[3]

$$\lambda = Gs,$$

s being the only parameter of the scattering process that sets a length (or m^{-2}) scale (s is the center of mass energy squared).

There is at present no experimental information that sets the length scale of the weak interactions. However there are two theoretical suggestions as to what the length scale might be.

1. The 'length' at the unitarity limit. If the weak interaction was pointlike all two body cross sections would rise like

$$\frac{G^2 s}{\pi} \tag{2}$$

and being pointlike only the S wave interaction is allowed. However, the unitarity limit for the cross section for S wave scattering goes as π/s, thus at a large value of s the weak interaction cross section must be modified to avoid a unitarity violation (at the energy $\sqrt{s_u} = \frac{1}{G}$). The length associated with this value of s (which was called the 'fundamental length' by Heisenberg) is

$$\ell_f = \frac{1}{\Lambda_u} = \frac{1}{\sqrt{s_u}} = \sqrt{G} \sim 10^{-17}\text{cm} \tag{3}$$

Note that, by definition, the dimensionless coupling constant

$$\lambda_u = Gs_u \simeq 1, \tag{4}$$

thus indicating that the weak interactions actually become 'strong' at these very high energies. It appears that the intrinsic strength and the range of force of the weak interactions are therefore intimately tied together. The interaction is strong in the sense that the S wave cross section is as large as any S wave cross section can be. (In strong interactions the low partial waves are strongly absorbed and thus the S wave cross section probably does not stay at the unitarity limit; thus at the unitarity limit the weak interaction cross section would likely exceed the strong interaction S wave cross section, however, the actual cross section would only be $\sigma \sim \frac{G}{\pi} \sim 10^{-33}\text{cm}^2$ compared to $\sim 3 \times 10^{-26}\text{cm}^2$ for hadron scattering cross sections, because of the large number of angular momentum states excited in the hadron scattering.)

2. A second way to set the 'length' scale for weak interactions is to imagine that the exchange of a massive boson is responsible for the weak force between two particles.[4] The mass (M_W) of this hypothetical boson then sets the scale

$$\ell_W \sim \frac{1}{M_W} \tag{5}$$

and the coupling constant for the W coupling to say two leptons is semiweak and given by

$$g^2 \simeq GM_W^2 \simeq \lambda_W.$$

Thus the larger the mass M_W, the stronger the semiweak interaction becomes. This illustrates again that the fundamental nature of the weak interaction is presently indeterminate, there being a tradeoff between the strength and the range of the interaction. Experimentally it is, therefore, necessary to determine either the fundamental dimensionless coupling constant or directly measure the range of the interaction. Clearly measurement of a distance of 10^{-17}cm is a very ambitious undertaking since momentum transfers of $\sim(300)^2$ GeV/c^2 would be required. Nevertheless as discussed later we might contemplate observation of momentum transfers of $(30)^2$ within the decade, in forthcoming neutrino experiments allowing a probe of distance down to $\sim 10^{-16}$cm.

There have been other suggestions as to a fundamental length of weak interactions in terms of the exchange of scalar bosons and a variety of other postulated particles.[5] These particles were invented to provide a renormalizable theory of weak interactions.[5]

Recently a dispersion theoretic approach has been applied to the question of the high energy behavior of weak interactions starting with the posthumous paper by Pomeranchuk.[6,7] Other calculations have followed this lead.[8] There are no firm conclusions to be drawn from such analyses but some very interesting speculation about the processes that may dominate the weak interactions at high energy are made. Also, as shown by Pomeranchuk,[6] if the weak interaction becomes long ranged at high energy with a cross section that approaches that of strong interactions, such a behavior cannot set in before an energy of the unitarity energy $\sqrt{s_u}$. Dolgov, Okun and Zakharov have attempted a dispersion theoretic estimate of the lower limit of the contribution from higher order weak diagrams for lepton-lepton collisions.[8]

Other theoretic attempts at handling the higher order weak interactions have focused on a summation of the contributions from all higher order diagrams.[9,10] The first such attempt known to us was made by Feinberg and Pais and more recently by Arbuzov.[9]

An interesting proposal for modifying the weak interaction was made by Gell-Mann, Goldberger, Kroll and Low.[11] Their proposal would lead to a modification of the universality of first order weak interactions such that the diagonal and nondiagonal lepton-lepton processes would proceed with different rates.

Many other suggestions have been made for calculating the higher order diagrams or for formulating a renormalizable theory of weak interactions. (See Refs. 12, 13, 14, 15, 16 for an incomplete list).

A promising way to separate (or estimate) the range and 'intrinsic' strength of the weak interaction is through the observation of a certain class of higher order weak interaction processes. While the validity of such calculations is certainly not proved, as order of magnitude estimates these calculations make some sense, especially when applied to pure leptonic systems.[15,16,17,18,19] If higher order weak processes are suppressed in all systems relative to first order processes then the observation of higher order weak processes will likely be carried out with low energy weak interaction processes such as a rare decay mode of K mesons because of the possible large abundance of such decay particles.

At the same time study of high energy weak interactions bring us closer to the unitarity limit where we expect surprises. These studies will likely be carried out with high energy neutrino beams or colliding lepton beams. In fig. 1 we attempt to summarize the present and projected range of energies available for weak interaction studies as well as the present range of transition rates that have been studied for K decays, in particular, in this figure we attempt to show the regions in these variables where new surprises in the weak interaction might be expected. The moral to be gained from this graph is that already experiments have covered a large range of energy and transition rates and we are close to the regions where surprises might be expected.

A short summary of the experimental measurements needed to 'unravel' the range and 'intrinsic' strength of the weak interaction is in order. The 'intrinsic' range and 'intrinsic' strength are assumed to be tied together in such a way that

$$G \sim g^2 \cdot 1/(m_\ell)^2 \qquad (6)$$

where g is the intrinsic coupling strength and m_ℓ is a mass that characterizes the range of forces.

There are basically three ways to detect or measure the value of m_ℓ

1. Study <u>high momentum</u> transfer processes observing the effects of m_ℓ in the form factor

$$\frac{d\sigma}{dq^2} \alpha \frac{1}{[1 + \left(\frac{m_\ell}{q}\right)^2]^2} \qquad (7)$$

2. Study <u>very high energy</u> scattering; in the vicinity $\sqrt{s} \sim m_\ell$ where higher partial waves will enter the weak interactions and a 'break down of locality' will occur.
3. Observe processes that can only proceed by 2nd or higher order weak interactions and assume (on the basis of the perturbation theory

allogrim) that the rate for such processes related to that for first order processes is, order of magnitude,

$$\frac{\Gamma(\text{2nd order})}{\Gamma(\text{1st order})} \sim G^2 m_\ell^4. \tag{8}$$

In a more careful perturbation calculation the ratio of second to first order rates becomes[19]

$$\xi^2 = \frac{G^2 \Lambda^4}{32\pi^4} \tag{9}$$

where Λ is a cut off mass that is used to remove the divergence of the integrals associated with second order contributions. For nonleptonic or semileptonic processes these calculations assume that the range or size of the strong interactions does not provide a cutoff to the integral.[15,20] Such an assumption can be justified on the grounds of current algebra or the quark model or any model where the weak current couples to pointlike objects inside the hadron (like the parton model).[21,22] However, this assumption does seem to violate simple minded intuition that the hadrons can not generally support high momentum transfers. Recent observations of inclusive processes where hadrons appear to be capable of supporting high momentum transfers,[24] can be explained by parton or quark pointlike structures.[22,23] However, it is not clear that pointlike structure is <u>necessary</u> to explain this phenomena (nor in fact that it is really sufficient) and more mundane explanations of the deep inelastic scattering have been proposed.[25] Therefore, it is not presently clear that the higher order processes are not cut off by the strong interaction in semileptonic or nonleptonic processes. For this reason it is very important that leptonic processes be studied.

Experimentally techniques 1 and 2 require high energy particles and the possibilities for such studies are only now becoming available with the advent of high energy machines such as NAL and the CERN 300 GeV machine. In practice such studies will likely be carried out using high energy neutrino beams.

The direct observation of higher order weak processes will likely depend on the intervention of a selection rule in first order weak interactions that are violated by the higher order processes. However, in some cases it may be necessary to separate higher order weak processes from first order contributions by observing the nonlocality generated by the higher order process.[26,27] Generally, therefore, the detection of higher processes will only be as sensitive as the validity of the selection rule. So far the best obeyed selection rules appear to be the absence of neutral currents in semileptonic processes and the $|\Delta S| < 2$ rule for nonleptonic processes.[28] In the next section we review the present status of the selection rules obeyed by the weak interaction.

It is interesting to note the different dependence on m_ℓ in techniques 1 - 3. For 1 and 2 the larger m_ℓ the more difficult it becomes to 'measure' m_ℓ (or to detect a deviation from $m_\ell \to \infty$). However, for the higher order corrections, especially for lepton-lepton collisions, the larger m_ℓ the easier it is to 'measure' m_ℓ. Of course perturbation intuition may fail here but if it does not then these techniques are complementary and should all be pursued. For example, it is difficult to foresee in the near future experiments that attain momentum transfers of $(300)^2$ GeV/c^2 and therefore $m_\ell \sim 300$ GeV would be hard to observe by techniques 1 or 2. However, for $m_\ell \sim 300$ GeV the higher order corrections become maximal and might be detected eventually in e^+e^- collisions as discussed below.

In table 1 we have attempted to summarize the present guesses for the limit on Λ from various viewpoints, the low values of Λ all come from semileptonic processes or nonleptonic processes. This table might be viewed in the following way; there are hints that the weak interaction cutoff is low and therefore something interesting is expected to occur in weak interaction processes for $\sqrt{s} \lesssim 10$ GeV. Also if the weak force is transmitted by an intermediate vector boson the mass is expected to be relatively low compared to the unitarity limit. However, these speculations are based on calculations that in all cases involve hadrons in the weak process. It may still be that the low values of Λ in table 1 are (i) determined by the strong interaction range or (ii) that perturbation theory is not relevant. To answer the first question will require the study of leptonic processes at large s. Probably the answer to question (ii) will require study of weak interaction processes very near $s \sim 1/G$.

The plan of this paper is essentially spelled out in the index. We first review the status of various weak interaction selection rules and discuss briefly the prospects for detecting intermediate vector bosons in the near future. The rest of the paper is broken up into sections that are classified by the kinds of particles that participate in the weak process. Each section deals with the processes suitable for detecting higher order weak processes or the high energy behavior of the weak interaction for that particular system.

a. Status of Various Selection Rules

The selection rules in weak interactions are not presently required by any basic theory; the rules being almost completely empirical. For this reason it is not known how exact such rules should be, and in fact some selection rules are known to be broken at the 5% level in the amplitude. However, some selection rules are suspected to be exact in first order weak interactions, but perhaps broken in higher orders. If this is true then the observation of a violation of the rule would be a signature for higher order processes; but, it need not be since the rule might simply be broken by the first order weak interaction. Since the observation of the violation of CP invariance, we know that sometimes very small violations in weak amplitudes (or super weak) can occur, and perhaps small violations of other selection rules might equally be observed. However, in the case of the absence of neutral semileptonic currents ($\Delta Q = 0$, $\Delta S \neq 0$ processes), the upper limit on the violation has now been shown to be three orders of magnitude lower than the CP violation rate,[29] perhaps indicating that the absence of neutral currents is a better selection rule than CP invariance.

In table 2 the current upper limits on the amount of violation for weak amplitudes for the selection rules is presented for:

$\Delta Q \neq 0$	leptonic processes
$\Delta Q \neq 0$	semileptonic processes
$\Delta S = \Delta Q$	semileptonic processes
$\Delta S < 2$	semileptonic processes
$\Delta S < 2$	nonleptonic processes

A notable point in this table is the absence of any useful limit on the $\Delta Q \neq 0$ selection rules for purely leptonic systems. Remarkably, the only well tested selection rule is the $\Delta Q \neq 0$, semileptonic rule, and only for the $\Delta S \neq 0$ subclass.

The $\Delta T = 1/2$ selection rule is now known to be broken by about 5% in the amplitude for several processes suggesting that the rule is only approximate in <u>all</u> cases. We, therefore, neglect this rule in table 2. Similarly, second class current in semileptonic amplitudes may come in at the same level.

One moral that might be drawn from table 3 is that when searching for higher order weak processes, violations of the ($\Delta Q \neq 0$, semileptonic) rule would be more likely to pay off because the other selection rules have yet to be tested to a sensitive level. For example, if the higher order processes come in at the relative amplitude level of 10^{-6}, this is 4-5 orders of magnitude in the amplitude lower than these selection rules have been tested, but only one or two orders below the ($\Delta Q \neq 0$, $\Delta S \neq 0$ semileptonic) rule. Even if the second order process comes in (1-2) orders of magnitudes below a primitive neutral current, it might still be possible to separate the higher order process as discussed below.

b. Detection of Intermediate Vector Bosons

The discovery of one or more bosons that couple semiweakly to leptons and hadrons and thus are candidates for the 'mediators' of weak interactions would go a long ways towards answering the basic questions about weak interactions posed in the introduction. Thus the search for such hypothetical but crucial states is of great importance and experimenters are well aware of this as can be proved by looking at the current proposals for experiments at the NAL.[32]

With the advent of high intensity neutrino beams at NAL or CERN it should be possible to produce, in a massive detector, adequate numbers of W vector bosons to discover such a particle if the mass is below $\sim$ 12-15 GeV.[33] It also appears that the boson can be detected independent of the relative branching fraction into leptonic and hadronic final states and, therefore, a conclusive search can be made in this mass range.[34]

Higher mass bosons might be detected in hadronic or photonic interactions at NAL or CERN up to the mass of 30-40 GeV, provided the cross sections for the production are comparable to the estimates of Lederman and Pope and provided the boson decays via the leptonic decay mode.[35] We emphasize that in the range of 15-40 GeV it will likely be impossible to conclusively exclude the existence of the intermediate vector boson because of the uncertainty of production cross sections and decay rates. Thus, up to ∿ 15 GeV an exhaustive search can be made and if conditions are favorable a W of mass 15-40 GeV could be detected.

The observation of a scalar charged meson is virtually impossible due to the expected small production cross section and the suppression of the leptonic decay mode.[36] If neutral vector bosons exist (perhaps producing so far undetected neutral leptonic current processes) and have any mass above the kaon mass, they likely would not have been detected up to the present. A neutral W° could be produced in e^+e^- collisions, but sensitive experimental searches have yet to be carried out in these processes.[37] It has been proposed to search for the existence of W° bosons using the process $e^+e^- \to \mu^+\mu^-$.[38] This search should be sensitive to the existence of any W° boson with mass below 8 GeV using colliding beam facilities such as SPEAR.[38]

2. Lepton-Lepton Collisions

Without the obscuring effects of the strong interactions, lepton-lepton scattering provides a 'clean' study of weak interactions. Experimentally, the detection of weak lepton-lepton processes is just coming into the range of experimental feasibility. There are basically three kinds of processes that may yield practical and interesting results:

$$\nu_\ell + z \rightarrow \ell + \bar{\ell} + \nu_\ell + z \tag{10}$$

$$\nu_\ell + \ell \rightarrow \nu_\ell' + \ell' \tag{11}$$

$$e^+ e^- \xrightarrow{\text{weak}} \mu^+ \mu^- \tag{12}$$

Study of the first two processes is becoming feasible because of the advent of high energy-high intensity neutrino beams at NAL and CERN. The s available to such processes, however, is likely to be limited to the range

$$s \sim 2m_e E_\nu \lesssim 5 \times 10^{-1} \text{ GeV}^2$$

For processes like 10 the requirements of coherence limits the mass of the three leptons to equally small values. Process 12 is the only one where values of s can be obtained where surprises and perhaps departures from the standard lowest order weak interaction theory may occur. In this case, s values in the vicinity of

$$s \sim 10 - 64 \text{ GeV}^2$$

might be attained with storage ring machines that are presently being constructed.

Unfortunately, since weak interactions are in general overwhelmed by electromagnetic interactions in process 12, a special dispensation is required to observe weak interactions. It has been recently speculated that such a dispensation may occur under special circumstances at colliding beam facilities such as SPEAR.[38]

a. Deviations from the Universal V-A Theory in Lowest Order--the Diagonal Coupling

Gell-Mann, Goldberger, Kroll and Low[11] have suggested a theory of weak interactions in which the leading divergences occur only in the diagonal interactions (i.e. $(\nu_e e)(\nu_e e)$ terms), which are thus speculated to be quite unconnected with the off diagonal interactions (i.e. $(\nu_e e)(\nu_\mu \mu)$ terms). Thus, higher order weak corrections may be manifested in a resulting difference between the diagonal and off diagonal coupling constants, which in turn would be observable in $s \to 0$ processes. In order to test this idea it will be necessary to compare processes like

$$\nu_\mu + \mu^- \to \nu_\mu + \mu^- \tag{13}$$

$$\nu_e + e^- \to \nu_e + e^- \tag{14}$$

with processes like

$$\nu_\mu + e^- \to \mu^- + \nu_e \tag{15}$$

Fortunately, these processes will likely be measured in the near future and the issue can be resolved.

Observation of process (14) may be accomplished in neutrino experiments currently underway at CERN using the Gargamelle bubble chamber or in early experiments at NAL using the 15' bubble chamber filled with neon.[39]

Reaction (13) is the most problematic since free muon targets do not exist in nature. A convenient substitute for this process is the process[40]

$$\nu_\mu + z \to \mu^+\mu^-\nu_\mu z \tag{16}$$

This process can likely be detected also at NAL and the Harvard-Penn-Wisconsin Collaboration experiment (E1A) has been designed with this process in mind. I will not go into detail concerning the projected experimental difficulties in studying this process since Professor Mann has described this in his talk. If this process can be separated from background at NAL, it should be possible to make a 10% measurement of the cross section. Incidentally, the calculations of the rate for process (16) are presently only good to $\sim$ 10%.[40]

We must emphasize, however, that the bulk of the events detected at NAL, even though the neutrinos are high energy, will likely have a low $\mu^+\nu_\mu$ invarient mass and thus the study of process (13) via (16) is at small s.[33,40] Nevertheless, it should soon be possible to experimentally compare the diagonal and off-diagonal coupling constants at low s and thus decide on the GGKL conjecture.

b. Psuedo Neutral Leptonic Currents

(i) Spacelike

At present there is no evidence to support the absence of first order neutral currents coupled only to leptons (see table 2). Recently it has been conjectured by Weinberg and others that such currents could exist in a renormalizable theory of weak and electromagnetic interactions.[13]

The most convenient processes to use to search for neutral leptonic currents in first order are

$$\nu_\mu + e^- \rightarrow \nu_\mu + e^- \qquad (17)$$

$$\nu_\mu + z \rightarrow e^+ e^- \nu_\mu z \qquad (18)$$

Again process (17) is on the verge of detectability in present or near future experiments. For example, process (17) can perhaps be detected in the present CERN studies with Gargamelle if the cross section is no less than $\sim$ 5 times smaller than the present limit on this process.[41] The present limit on the cross section for (17) relative to the cross section expected for process (14) (on the basis of the universal V-A theory) is[42]

$$\frac{\sigma(\nu_\mu + e^- \rightarrow \nu_\mu + e^-)}{\sigma(\nu_e + e^- \rightarrow \nu_e + e^-)} < 0.4 \qquad (19)$$

The lower limit of this ratio predicted by the theory of Weinberg is[13]

$$\frac{\sigma(\nu_\mu + e^- \rightarrow \nu_\mu + e^-)}{\sigma(\nu_e + e^- \rightarrow \nu_e + e^-)} \geq 0.125 \qquad (20)$$

The search for process (17) in the neon bubble chamber at NAL is likely to be even more definitive. The study of process (18) is problematic because of the large background of Dalitz pairs in neutrino collisions.

If process (17) is not detected at the level of first order weak in bubble chambers it becomes interesting to see at what level the higher order corrections may come in and if the resulting cross section can be measured by massive target-counter techniques. An estimate of the cross section for process (17) proceeding through second order weak processes and assuming that the weak interaction cutoff is at the unitarity limit ($\Lambda \sim \sqrt{s_u}$) gives[19]

$$\sigma(\nu_\mu + e^- \to \nu_\mu + e^-) \simeq 1.5 \times 10^{-44} (E_\nu) \mathrm{cm}^2/\mathrm{GeV}$$

where E_ν is the ν_μ energy in GeV. Using full design intensity of the NAL machine and a 500 ton Pb detector approximately 2 events of type (17) would be produced per day. Thus, in principle, a purely leptonic higher order weak process could be detected at NAL, provided the unitarity limit provides the weak interaction cutoff. We do not mean, to imply, however, that it is presently known how to separate these two events/day from the large background, but only that the process seems in principle detectable under favorable circumstances. Note, however, that even at this level the ratio of cross sections is

$$\frac{\sigma(\nu_\mu + e^- \to \nu_\mu + e^-)}{\sigma(\nu_e + e^- \to \nu_e + e^-)} \sim 10^{-3}$$

and thus the resulting limit on first order weak neutral currents would only be at best $\sim 3 \times 10^{-2}$ in the amplitude. Thus, it appears difficult to put limits on the absence of first order neutral leptonic currents to the level that $\Delta S \neq 0$ semileptonic neutral currents have reached.

(ii) Timelike

Process (12) can proceed via weak interactions in several speculative ways: (1) direct channel production of a W° on the mass shell; (2) a first order weak neutral current coupling of the form $(ee)(\mu\mu)$; (3) an induced neutral current coming from higher order weak interactions.

Experimentally, the detection of any of these weak processes requires a suppression of the dominant electromagnetic amplitudes and a unique signature for the weak process. It appears that a sizable suppression of the first order electrodynamic contribution can be obtained if the initial leptons in process (12) are highly polarized in opposite transverse directions. A 'hole' appears in the angular distribution of the outgoing muons at favored values of θ and ϕ ($\cos\theta = \hat{p}_\mu \cdot \hat{p}_e$, $\cos\phi\sin\theta = \hat{p}_\mu \cdot \hat{a}$, where $\hat{a}$ is a unit vector along the e^- polarization vector).[38,43] This 'hole' is illustrated in fig. 2 as the ratio of the differential cross section for reaction (12) for completely polarized initial leptons to the cross section for unpolarized initial leptons, and in fig. 3 in a projection drawing of the differential cross section for the two cases. At the bottom of the 'hole' should be a sensitive place to search for any anomolies in process (12) including a weak interaction process.[38] In particular the μ longitudinal polarization will likely be sensitive to interference between first order EM and perhaps weak amplitudes. The polarization will be enhanced in the 'hole'.[38,44] It is too early to conclusively conclude that amplitudes can be uniquely extracted in this way, but there seems to be an intriguing possibility here that should be pursued. It seems very likely that the existence of a W° boson with mass below ~ 8 GeV could be directly observed in this way.[38] Careful theoretical calculations of this polarization and the background from higher order EM processes would be very useful in planning experiments.

3. Semi-leptonic Processes

a. Second Order Weak K Decays

The studies of K meson decays over the past two decades have provided a rich field for the study of nature and the weak interaction. Nearly every symmetry principle of particle physics has been successfully tested or found to be violated using K meson decays. The primary reason for this richness of the K meson system is due to the large mass of the Kaon relative to the leptons and π mesons. It is fortunate indeed that K mesons exist. Higher order corrections could, in principle, show up in any K decay including the nonleptonic decays. If the intrinsic coupling constant were large then the higher order corrections might be of comparable magnitude to the first order processes. For this reason exhaustive searches for rare decay modes of K mesons is of considerable importance. Any rare decay that is observed with an anomalous rate relative to the best theoretical guesses for the rate based on first order theory, is a candidate for evidence concerning higher order weak processes. In fig. 4 is shown the branching fraction levels to which exhaustive searches for rare decays have been made. In this figure are examples of processes with the lowest branching ratios that have been presently studied. As a rough rule of thumb exhaustive searches for rare K^+ decay modes have been extended down to a branching ratio of $\sim 10^{-5}$ to 10^{-6}.[45] For K_L^o decays the corresponding branching ratio is $\sim(10^{-3}$ to $10^{-4})$ and for K_S^o mesons the branching ratio is only $\sim(10^{-2}$ to $10^{-3})$. For K^- mesons the branching ratio is $\sim 10^{-2}$, however, CP invariance requires the K^+ and K^- decay ratios to be the same and the results from K^+ decays can then be inferred for K^- decays. In some cases it is possible to relate K_L^o and K^+ decays of K_S^o and K^+ decays and therefore the results for K^+ decays can be applied to the K_L°, K_S° decays.

Recently searches for special individual rare decay modes have been extended down to the branching ratio of $\sim (10^{-8}$ to $10^{-9})$.[29] Although only a few experiments of this kind have been attempted we may hope that the branching ratios region of 10^{-6} to 10^{-10} will be searched considerably more in the future. The advent of high intensity $K^\pm$ and K° beams at the AGS and the Bevatron will be the key factor in these studies.

The study of rare decay modes of K mesons therefore naturally divides into two parts. Studies of the branching ratio region of 10^{-2} to 10^{-6} where nearly exhaustive searches for all rare decay modes have been made and the branching ratio of 10^{-6} to 10^{-10} where studies are just beginning.

It appears that no important surprises are found in the K decay processes observed down to the level of $\sim 10^{-6}$. It seems likely that the higher order processes are not important in this region.

At lower levels the search for HOW processes has been associated with the $\Delta Q \neq 0$ selection rule and this seems to be the logical place to push for definitive evidence of HOW processes. The most important decay processes in this respect are

$$K_L^\circ \rightarrow \mu^+\mu^- \qquad (13)$$

$$K_S^\circ \rightarrow \mu^+\mu^- \qquad (14)$$

$$K^+ \rightarrow \pi^+e^+e^- \qquad (15)$$

$$\rightarrow \pi^+\mu^+\mu^- \qquad (16)$$

$$\rightarrow \pi^+\nu\bar{\nu} \qquad (17)$$

$$K_L^\circ \rightarrow \pi^\circ e^+e^- \qquad (18)$$

In the first four cases the decay can also proceed through a first order weak and first or second order electromagnetic transition. Unless interference is invoked between the HOW and the electromagnetic processes, these processes can only be used to search for HOW amplitudes down to the level of the electromagnetic amplitudes. In both processes 13 and 15 the present experiments have approximately reached the level where the E.M. processes should be seen. These processes will probably not be useful to pursue the search to lower levels unless something is amiss in our present understanding of the electromagnetic corrections.

Processes 17 and 18 are likely to provide the most sensitive way to unambiguously search for HOW processes and push lower the limit $\Delta Q = 0$, $\Delta S \neq 0$ currents. The first order weak-electromagnetic amplitude for process 17 is expected to be highly suppressed due to the zero charge of the neutrino. However since the neutrino is likely to have distribution of charge the amplitude does not vanish. A crude guess is that the rate for this process should be at least down by $q^4 \cdot \langle r^2 \rangle^2$, where r is the electromagnetic radius of the neutrino. The best guess for $\langle r^2 \rangle$ is $\sim 10^{-32} cm^2$ and for $q^2 \sim m_\pi^2$ we obtain a suppression factor of 10^{-12} in the rate.[46] Thus process 17 should be safe as a signature for HOW or neutral currents down to a branching ratio of $\sim 10^{-18}$.

The electromagnetic contribution to process 18 is likely to be strongly suppressed because CP invariance forbids the single photon intermediate state contribution to this process.[26] The lowest order E.M. process will then be due to diagrams with two photon intermediate states. We can crudely estimate the lower limit due to such contributions using a recent experimental limit on $K^+ \to \pi^+\gamma\gamma$[45]

$$\frac{\Gamma(K_L^\circ \to \pi^\circ e^+ e^-)}{\Gamma(K_L^\circ \to \text{all})} \lesssim \alpha \frac{\Gamma(K^+ \to \pi^+\gamma\gamma)}{\Gamma(K^+ \to \text{all})} \sim 10^{-5} \cdot 2 \times 10^{-5} \sim 10^{-10}.$$

Using current theoretical estimates for the rate of $K^+ \to \pi^+\gamma\gamma$ we find a branching factor of $\sim 10^{-12}$ or less.[45] The contribution coming from CP violation in the first order weak process is expected to be much smaller.

Experimentally, process 17 has been searched for in two experiments each covering a different region of the available phase space.[45,52] The best limit for the process that is independent of the behavior of the matrix element is $\sim 4 \times 10^{-5}$ at the 90% confidence level.[45] If a phase space or V-A matrix element is assumed the limit is reduced by an order of magnitude.[52] It seems feasible to search for this process, in the near future down to the level of $\sim 10^{-10}$.

Process 18 has yet to be searched for in any definite way. Considering all factors this process is likely the best candidate for a realistic search for HOW process if the branching ratios are below 10^{-9}.

It is possible to estimate the rate for processes 17 and 18 due to HOW in perturbation theory as discussed in the introduction. Primakoff has estimated that[19]

$$\frac{\Gamma(K \to \pi\nu\bar{\nu}, \pi^\circ \ell\ell)}{\Gamma(K \to \pi\ell\nu)} \sim 8\xi^2 \cos^2\theta_c$$

where θ_c is the Cabbibo angle. If these processes are not detected before 10^{-12} in this ratio, Λ the resulting cutoff would be reduced to ~ 1 GeV.

b. <u>Interference Between Second Order Weak Amplitudes and Others</u>

A possibly more sensitive technique to search for HOW is to observe a large sample of events of the kind

$$K^+ \to \pi^+ e^+ e^- \qquad (15)$$

that likely proceeds dominately through first order weak-first order E.M. processes. An asymmetry in the momentum spectrum of the e^+ and e^- could come about because of the HOW amplitude interfering with the lowest order process. Estimates of this effect have been presented in reference 27. Until process 15 is experimentally observed, it is impossible to estimate the experimental feasibility of this approach.[47]

c. <u>Production of Leptons in Hadron Collisions (NN $\rightarrow$ (ℓ,ν) + hadrons)</u>

If (ℓ,ν) lepton pairs were observed in hadron collision direct evidence for weak transitions in these processes would be obtained. Lederman has suggested that at a high energy pp colliding beam facility it might be possible to observe such processes.[48] He has used an analogy with the process pp $\rightarrow$ (ℓ,ℓ) + hadrons and attempted to extrapolate available data at low energies to these very high C.M. energies. Provided this all works, we might expect that high mass (ℓ,ν) pairs would be produced. In fact it might be possible to obtain events where

$$m_{\ell\nu}^2 \sim s_u .$$

Since the lepton system is at the same s as the unitarity limit we might expect appreciable (perhaps observable) HOW amplitudes.

4. Non-leptonic Processes

(a) Violation of Selection Rules

As can be seen from table 3, the only important selection rule for nonleptonic processes seems to be the $\Delta S < 2$ rule. The only obvious way to search for HOW non-leptonic amplitudes is to search for $\Delta S \geq 2$ transitions. The only experimentally detected non-leptonic processes with $\Delta S > 0$ are kaon and hyperon decays. The only $\Delta S \geq 2$ kaonic process is the interaction responsible for the K_S° - K_L° mass difference. It is presently thought that the mass difference is due to HOW which break the $\Delta S < 2$ rule. Unfortunately, the mass difference is only one very small number and it has not yet been calculated reliably. The search for other HOW amplitudes is likely to be best accomplished by looking for the decays of $|S| > 1$ hyperons into $S = 0$ final states. For example:

$$\Xi^- \to n\pi^- \quad (\Delta S = 2) \tag{19}$$

$$\Xi^\circ \to p\pi^- \quad (\Delta S = 2) \tag{20}$$

$$\Omega^- \to \pi^- n \quad (\Delta S = 3) \tag{21}$$

$$\to \pi^- \Lambda \quad (\Delta S = 2) \tag{22}$$

With the advent of high energy proton beams it becomes feasible to produce copious high energy hyperon beams. Process (20) is the easiest to detect because of the two charged particles in the final state and the characteristic Q value of the process relative to $\Lambda \to \pi^- p$ decay. There is an approved experiment at NAL which will likely be sensitive to this process.[49] It has been estimated that a branching ratio limit of $\sim 10^{-8}$ can be reached within a modest running time if the NAL machine runs at design intensity.[50] March estimates that a limit of $\sim 10^{-10}$ might eventually be achieved.[50]

Theoretical estimates of the possible HOW contribution to these processes seem to be nonexistent and would be appreciated.

b. CP Violation as 2nd Order Weak

In the Wolfenstein superweak theory of CP Violation, the violation occurs in the mass matrix with $\Delta S = 2$. It seems to us quite possible (but we know of no theoretical suggestions along this line) that the CP violation is a direct manisfestation of HOW processes.

5. High Energy Neutrino Scattering

Clearly the most likely place to observe departures from the expectations of conventional, lowest order weak theory is at large s, in neutrino scattering. It is fortunate indeed that under certain circumstances the hadronic systems in such collisions will likely behave as though they were massive, pointlike scattering centers. Thus we expect that very high momentum transfers can be achieved in early experiments at NAL and the CERN SPS.

As before we expect HOW process to lead to violations of certain selection rules in neutrino processes. In addition it may be possible to directly observe the nonlocality that HOW process may produce.

a. Electromagnetic Charge Radius of the Neutrino

The small distance behavior of weak interactions will be sensitively probed by observing the charge radius of the neutrino. The best guess for this radius leads to a cross section ratio of[46]

$$\frac{\sigma(\nu_\mu + N \to \nu_\mu + N)}{\sigma(\nu_\mu + N \to \mu^- + N)} \sim 10^{-5}$$

We would also expect by analogy that the contribution to deep inelastic ν_μ scattering would also behave the same way with

$$\frac{\sigma(\nu_\mu + N \to \nu_\mu + \text{all})}{\sigma(\nu_\mu + N \to \mu^- + \text{all})} \sim 10^{-5}$$

The process

$$\nu_\mu + N \to \nu_\mu + (\text{all}) \qquad (19)$$

could also arise from $\Delta S = 0$, $\Delta Q = 0$ first order semileptonic currents and from HOW induced neutral currents. Thus, we expect that the search for such induced currents will not be confused by EM processes (i.e. the ν_μ charge radius) unless the resulting cross section is only $\sim 10^{-5}$ of the charged current cross sections.

The measurement of the charge radius is in itself an interesting experiment. In order to separate the charge radius from the neutral currents the Z^2 behavior of the electromagnetic process would need to be observed.

b. Deep Inelastic 'Neutral' Currents

The SLAC experiments have given evidence that hadrons can 'act' point like if appropriate processes are studied (inclusive processes).[24] Using high energy neutrinos, and hitting these 'pseudo point like hadrons' allows very high momentum transfers in the lepton-lepton system. To the extent that the hadrons act point-like,the HOW divergent intergals may truly be cutoff by the weak interactions and not the hadronic size. It is thus possible that if the weak interactions cutoff is near $\sqrt{s_u}$ the HOW amplitudes may be relatively much larger than in the case of semileptonic decay processes. Thus, these processes may be almost 'lepton-lepton like'

Experimentally it would be necessary to study the processes

$$\nu_\mu + N \to \nu_\mu + (\text{all}) \tag{19}$$

and separate this from the large background of events

$$\nu_\mu + N \to \mu^- + (\text{all}) \tag{20}$$

In particular it would be necessary to prove that there is no μ^- in the final state. It is likely that this can be easily done in a Ne bubble chamber or the detector for E1A at NAL if the ratio of cross sections for these reactions is 10^{-2} - 10^{-3}.[39] Going to smaller ratios would likely require a major change of the experimental setup for E1A or the use of the Ne bubble chamber with an External Muon Identifier to reject a larger fraction of events of type (20).

Primakoff has estimated the ratio of these cross section to be[19]

$$\frac{\sigma(\nu_\mu + N \to \nu_\mu + \text{all})}{\sigma(\nu_\mu + N \to \mu^- + \text{all})} = 3\xi^2$$

for the integrated cross section. This ratio would likely be larger if only large q^2 (= $(p_\nu - p_\mu)^2$) events were used. For $\Lambda \sim \sqrt{s_u}$ we obtain a theoretical ratio of $\sim 10^{-3}$. Thus, if the weak interaction cutoff is at $\sqrt{s_u}$ and if the hadronic system in reaction (19) does not provide a cutoff of the divergent integral and if the cutoff procedure is valid, then the HOW induced process (19) will likely be observed at NAL.

c. Breakdown of Locality in Deep Inelastic Scattering

We now turn to a brief discussion of the possibility of direct locality tests in deep inelastic processes of the type[53]

$$\nu_\mu + N \to \mu^- + (\text{all}) \tag{20}$$

and thus the direct observation of the 'range' of weak interactions. We use the ordinary definitions of the variables for process 20

$$q^2 = 4E_\nu E_\mu \sin^2\theta_\mu/2$$

$$\nu = E_\nu - E_\mu$$

$$x = q^2/2\nu m_p; \; y = \nu/E_\nu$$

If scale invariance holds the differential cross section can be expressed entirely as a function of x and y. We assume that scale invarience holds and proceed to discuss locality tests (which test the locality at the lepton-lepton vertex if these assumptions are valid). We must distinguish two kinds of nonlocality in this regard.

(a) Type 1. In the $(\nu-\mu)$ system an orbital angular momentum of > 0 is observed. Tests for this kind of nonlocality were pointed out long ago by Lee and Yang.[51] These tests take on a particular significance when high momentum transfer collisions are studied. The most general expression for the differential cross section for inelastic neutrino scattering, if locality holds, is of the form

$$\frac{d^2\sigma}{dxdy} = G(q^2,x)\ f(y;x,q^2)$$

with $f = \sum_{n=0} a_n y^n$ and $a_n = 0$ for $n > 2$.

(b) Type 2. This is the type of nonlocality that comes from a meson propagating from the leptonic vertex to the hadronic vertex. The mesonic propagator is then expected to modify the differential cross section for deep inelastic scattering. If scale invariance holds it would then be possible to write the differential cross section as a product of three functions (taking the diffraction model)

$$\frac{d^2\sigma}{dxdy} = \frac{G^2}{\pi}\ M\ E\ [\nu\beta]\ [1 - y + y^2]\ [f(q^2)]$$

where, in particular we take the meson mass to be the W mass,

$$f(q^2) = \frac{1}{(1 + q^2/m_W^2)^2}\ .$$

This might allow us to search well above the mass range covered by the direct production of W's by neutrinos. If scale invariance is badly broken it would be difficult to use deep inelastic scattering to probe this form of nonlocality.

In fig. 5 is shown graphically the type of measurements that would be used to test for a breaking of the two types of locality. We have assumed that the NAL machine only runs at 200 GeV for this graph. In one case (q^2,x) would be fixed and the behavior of the resulting cross section with y would be studied. If y^3 or higher powers of y are needed to explain the data, evidence for nonlocality of type 1 would be obtained. In the second case (x,y) would be fixed and the resulting q^2 behavior of the cross section will be studied.

In fig. 5 is also shown the possible sensitivity of this probe of locality. Present tests of type 1 locality have reached the level of $\sim 10^{-13}$cm (in K-decay) whereas the experiment proposed here offers the possibility of studying distances of the order of 10^{-15}cm. An increase of two orders of magnitude in the locality check would clearly be of great interest.

We now briefly turn to the question of event rates for the deep inelastic process. We use as an example the predicted rates for E1A.[33] This detector which is schematically illustrated in fig. 6 will have a target mass of $\sim$ 400-500 tons. This is to be compared with the large H_2 bubble chamber at NAL with a target mass of $\sim$ 1 ton and the Ne filled chamber with a mass of $\sim$ 20 tons.

In table 3 we present the expected rates/day for events where $q^2 > 200$ GeV/c^2, under a variety of assumptions concerning the incident neutrino beam for 500 GeV/c protons in the machine. Even in the most pessimistic case an adequate number of events can be obtained to carry out the the locality test described above. Thus it seems likely that a definitive statement can be made concerning the range of weak interactions down to $\sim 10^{-15}$cm. With good luck and a 1000 GeV NAL proton beam perhaps 10^{-16}cm could be reached.

6. Summary and Conclusions

The short ranged behavior of the weak interaction is not presently known. Within the framework of conventional theory a pointlike interaction leads to divergent integrals which must be cutoff. It is probably necessary to consider different cutoffs depending on the type of process being investigated. For example, the cutoffs might be arranged as Λ_{NL}, Λ_{SL}, Λ_L denoting the nonleptonic, semileptonic and leptonic processes, respectively. We suggest that a further subdivision of the semileptonic taking into account the quasi-point-like behavior of the hadrons in deep inelastic processes. We denote this cutoff as Λ_{SLDI} for semileptonic-deep inelastic. Possibly this cutoff is more directly related to the Λ_L whereas the Λ_{SL} is more directly related to Λ_{NL}. However, arguments based on the Bjorken technique would likely not differentiate these cutoffs.

Within this framework we can summarize the conclusions of this paper

1. The search for $\Delta Q = 0$ semileptonic decay processes limits $\Lambda_{SL} \lesssim 15$ GeV. Reducing this limit further will require the search for $\Delta Q = 0$ processes that have strongly suppressed electromagnetic corrections. Two processes were suggested where the electromagnetic correction is likely sufficiently small to allow a limit on Λ_{SL} of ~ 1 GeV. The search for these processes requires new high intensity K beams.
2. The search for $\Delta Q = 0$ leptonic processes, in principle, allow an upper limit to be set on Λ_L of $\sim$(100-300) GeV. The experimental detection of such processes will be very difficult.
3. The search for $\Delta Q = 0$ semileptonic-deep inelastic processes will

probably allow an upper limit of $\sim$ 100 GeV to be set on Λ_{SLDI}. The experiment looks feasible at NAL either using the Ne bubble chamber or the massive calorimeter-target detector.

4. A lower limit on Λ_{SLDI} can likely be set by observing the resulting nonlocality (type 2). We guess that $\Lambda_{SLDI} > 30$ GeV can be obtained at NAL with the large calorimeter-target dectectors.
5. The existence of a W° with mass less than 8 GeV and a $W^\pm$ with mass less than (11-15) GeV can be determined using $e^+e^- \to \mu^+\mu^-$ and neutrino production, respectively. First order neutral leptonic currents at high Q^2 might also be detected in $e^+e^- \to \mu^+\mu^-$.
6. A breakdown of locality of type 2 in the weak interaction might be detected at high Q^2 using deep inelastic neutrino scattering.
7. A crude limit can be set on Λ_{NL} by searching for $\Delta S \geq 2$ decays.

Thus within this conventional picture it would be possible to bracket Λ_{SLDI} by $\Lambda_{SLDI} < 100$ GeV and $\Lambda_{SLDI} > 30$ GeV. This is about the best we can hope for. If $\Lambda_{SLDI} \sim \Lambda_{SL}$ then the present limits on Λ_{SL} would lead to interesting-observable nonlocal effects in the neutrino experiments.

The most exciting possibility is of course that totally new phenomena dominate weak interactions at large s and Q^2. In this regard neutrino microscopy also offers the exciting possibility of probing nature in the new region of small distances.

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44. J. D. Bjorken, private communication.

Table 1.

Present Information On The Weak Interaction Cut off

Λ	PROCESS	COMMENTS	AUTHORS
~ 2600 GeV	$\nu+\bar{\nu} \rightarrow W+\bar{W}$	Intermediate Boson theory	Gell Mann et al.[11]
~ 320 GeV	$\nu+e \rightarrow \nu+\mu$	Simple unitary limit	
< 100 GeV	$K^+ \rightarrow \pi^+ \ell \ell$	Cut off of divergent integral	Ioffe and Shabalin
~ 30 GeV	$\nu+\ell \rightarrow \nu+\ell$	Crossing symmetry included in calculation	Applequist and Bjorken[7]
≤ 14 GeV	$K_L \rightarrow \mu\mu$	Cut off of divergent intergrals using Bjorken technique	Ioffe and others[17] (LRL Experiment)[29]
$\Lambda \sim 8$ GeV	$K_S \rightarrow \pi\pi$	Soft π and K techniques	Glashow, Schnitzer and Weinberg[31]
$\Lambda \sim (4\text{-}8)$ GeV	$K_L - K_S$ Mass difference	Bjorken technique and cut off of divergent intergrals	Ioffe et al.[15,17] Mohapatra et al.[16]
$\Lambda \simeq$ Small	Rare Electro-magnetic decays of K mesons	Electromagnetic processes with virtual photon diverge quadratically	Geshkenbein and Ioffe[30]
$\Lambda \simeq$ Small	Nonleptonic decays	$f \sim G\Lambda^2 \sim 10^{-5}\text{-}10^{-6}$	
$\Lambda > 2$ GeV	W production	Assume $\Lambda \sim M_W$	CERN bubble chamber and counter experiments

Table 2

Selection Rule	Approximate limit on the Ratio of $\left(\frac{\text{Violating Amplitude}}{\text{Nonviolating Amplitude}}\right)$	Processes that Violate the Rule
$\Delta Q \neq 0$, leptonic	~ 1	$\nu_\mu + e^- \to \nu_\mu + e^-$
		$e^+e^- \to \nu_\mu \bar{\nu}_\mu$
		$e^+e^- \to \mu^+\mu^-$
$\Delta Q \neq 0$, semileptonic	$\sim 4 \times 10^{-5}$	$K_L^\circ \to \mu^+\mu^-$
$\Delta S \neq 0$	$\sim 10^{-3}$	$K^+ \to \pi^+e^+e^-$
	$\sim 3 \times 10^{-3}$	$K^+ \to \pi^+\nu\bar{\nu}$
$\Delta S = 0$	$\sim 5 \times 10^{-1}$	$\nu_\mu + n \to \pi^- p\ \nu_\mu$
$\Delta S = \Delta Q$, semileptonic	$\sim 10^{-1} - 4 \times 10^{-2}$	$K^\circ \to \pi^+e^-\nu$
	$\sim 10^{-1}$	$K^+ \to \pi^+\pi^+e^-\nu$
	$\sim 10^{-1}$	$\Sigma^+ \to ne^+\nu$
$\Delta S < 2$, semileptonic	~ 1	$\Xi^- \to ne^-\nu$
	~ 1	$\Omega^- \to ne^-\nu$
$\Delta S < 2$, nonleptonic	3×10^{-2}	$\Xi^- \to \pi^- n$
		$\Xi^\circ \to \pi^- p$
		$\Omega^- \to \pi^- n$
		$\Omega^- \to \pi^- \Lambda$

Table 3

Rate for Selected Deep Inelastic Scattering Events with $q^2 > 200 (GeV/2)^2$

(Based on the Parton Model)*

E_ν	Quad Focus H-R	No Focus H-R	Quad Focus CKP	No Focus CKP	Quad Focus H-R H_2 Target ($2\frac{1}{2}$ Tons
135-145	12	5	2	1	.2
145-155	67	28	10	4	.9
155-165	125	53	16	7	1.6
165-175	172	77	17	8	2.2
175-185	238	103	19	8	3.1
185-195	280	118	18	8	3.7
195-205	308	132	16	7	4.0
205-215	300	128	13	6	3.9
215-225	280	120	12	5	3.6
225-235	280	120	11	5	3.6
235-245	235	104	10	4	3.1
245-255	200	81	8	3	2.6
Total Events/Day					32.5 H_2 Target Rate
(192 Ton Detector)	2497	1070	152	66	
(20 Ton Detector)	260	107	16	6.6	

*Folding in the correct detection efficiency may drop all of these rates by factors of at least 2.

WEAK INTERACTIONS AT HIGH AND LOW ENERGIES

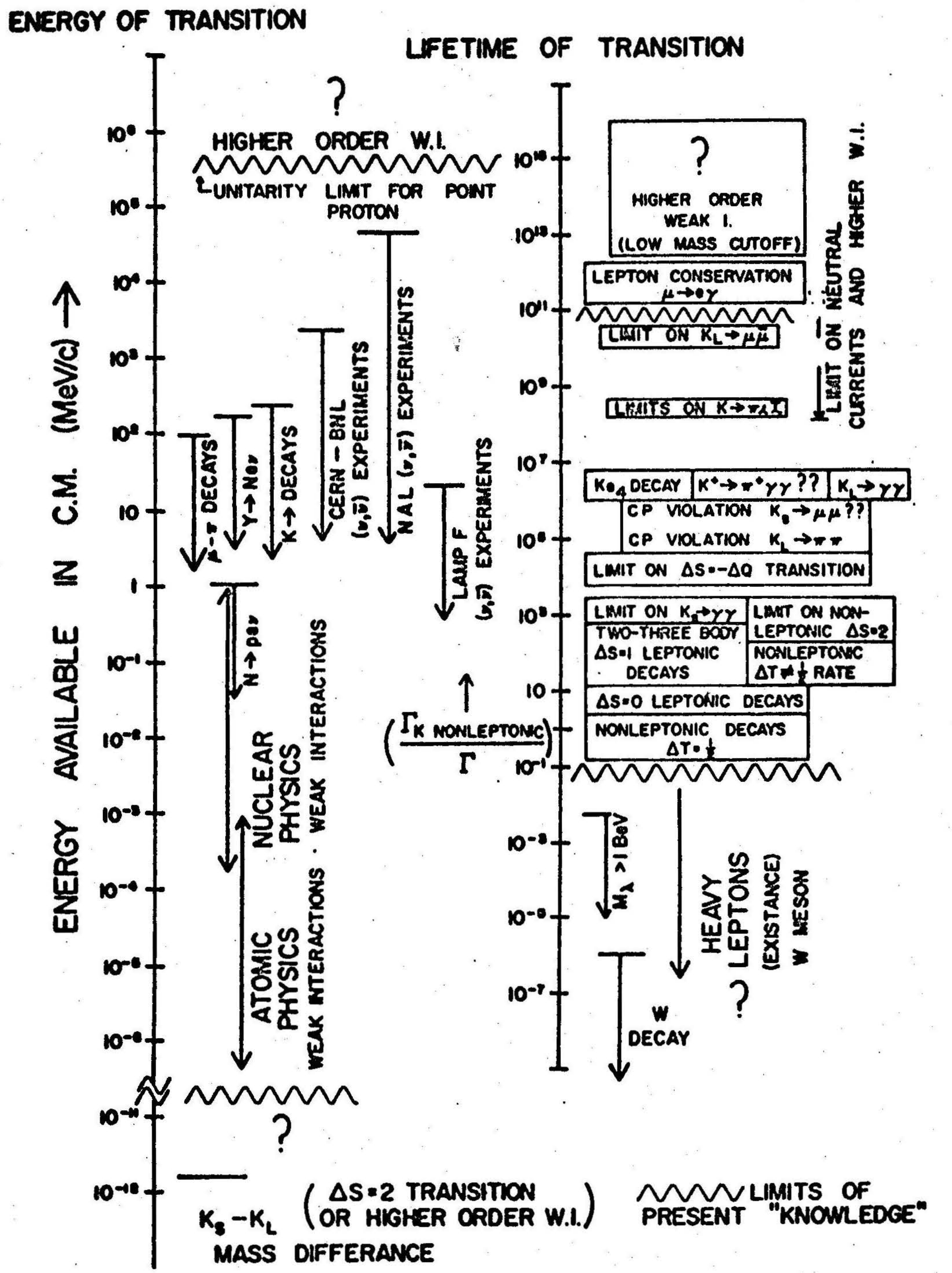
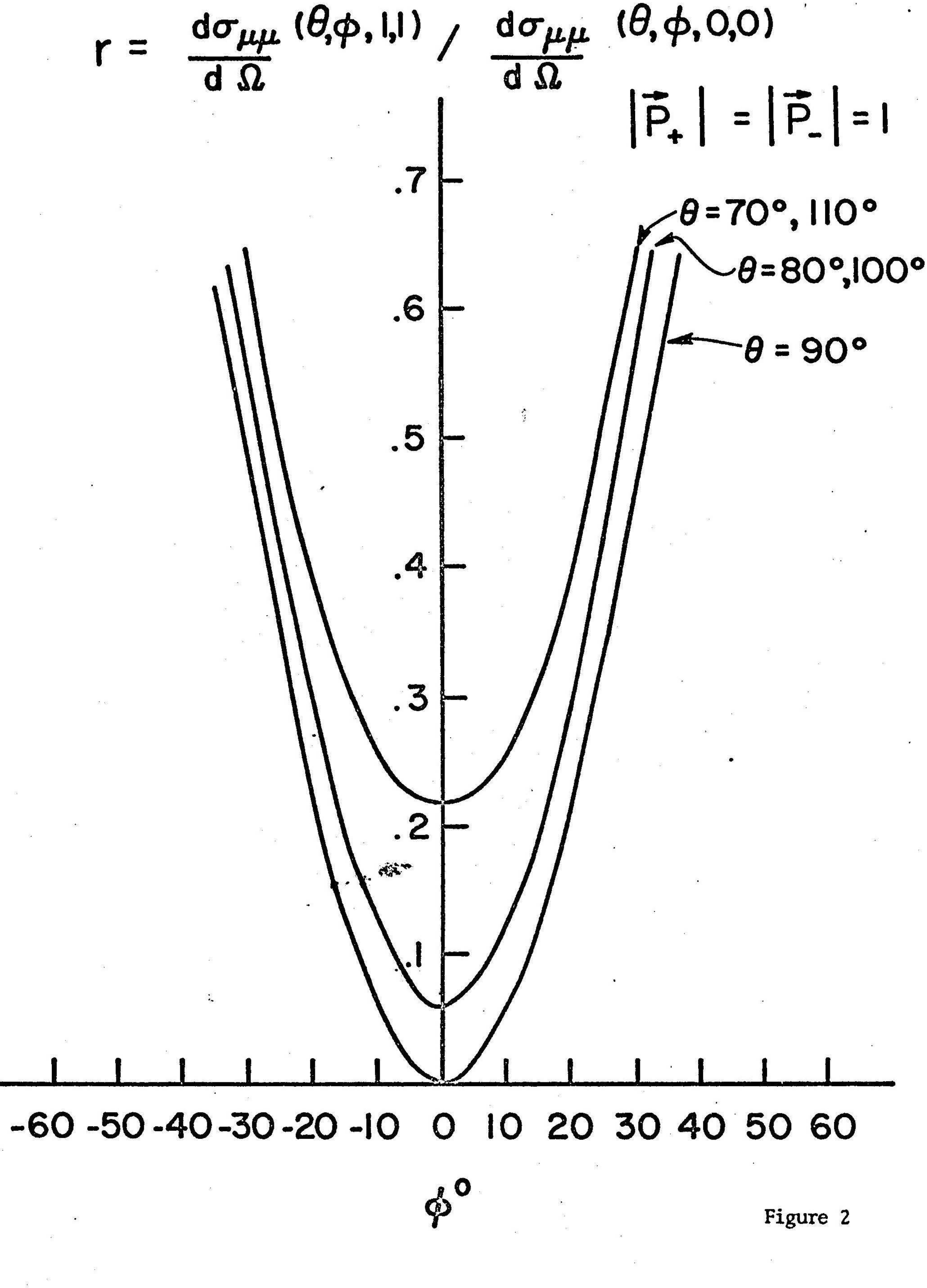


Figure 1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|P+| = |P-| = 1
θ=70°, 110°
θ=80°,100°
θ = 90°
.7
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.3
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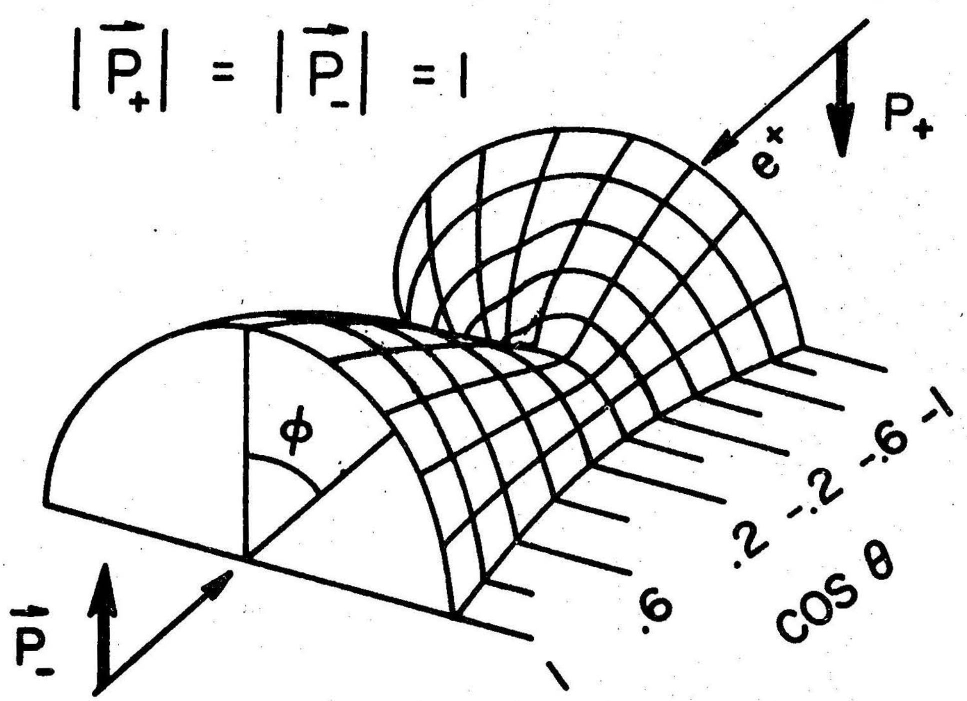
φ°

Figure 2



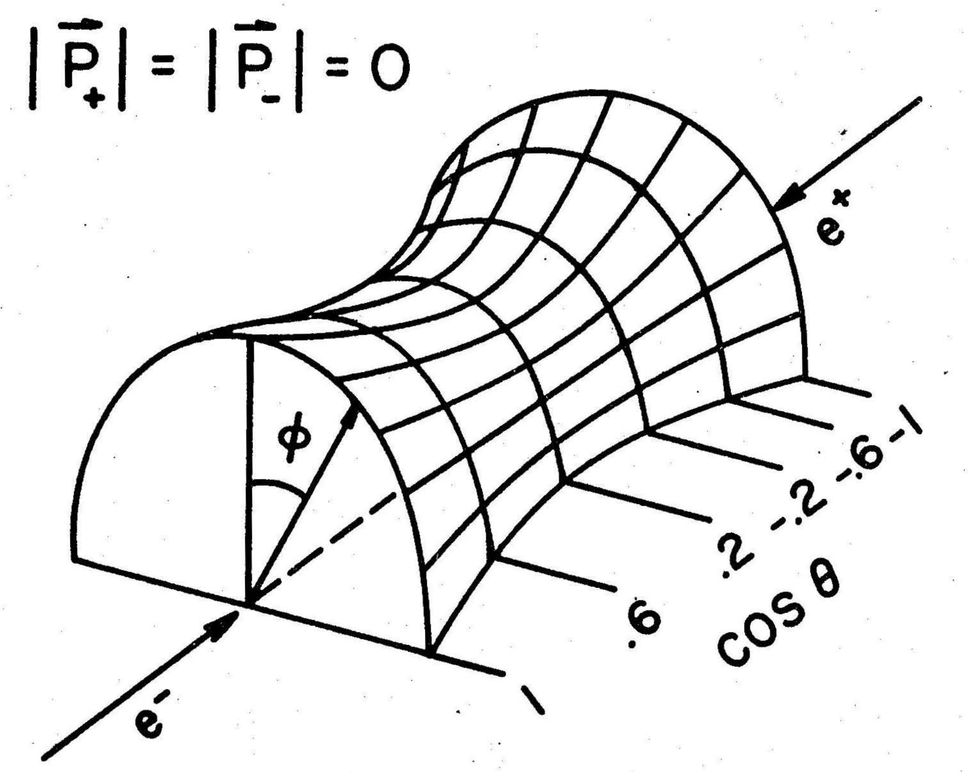


Figure 3

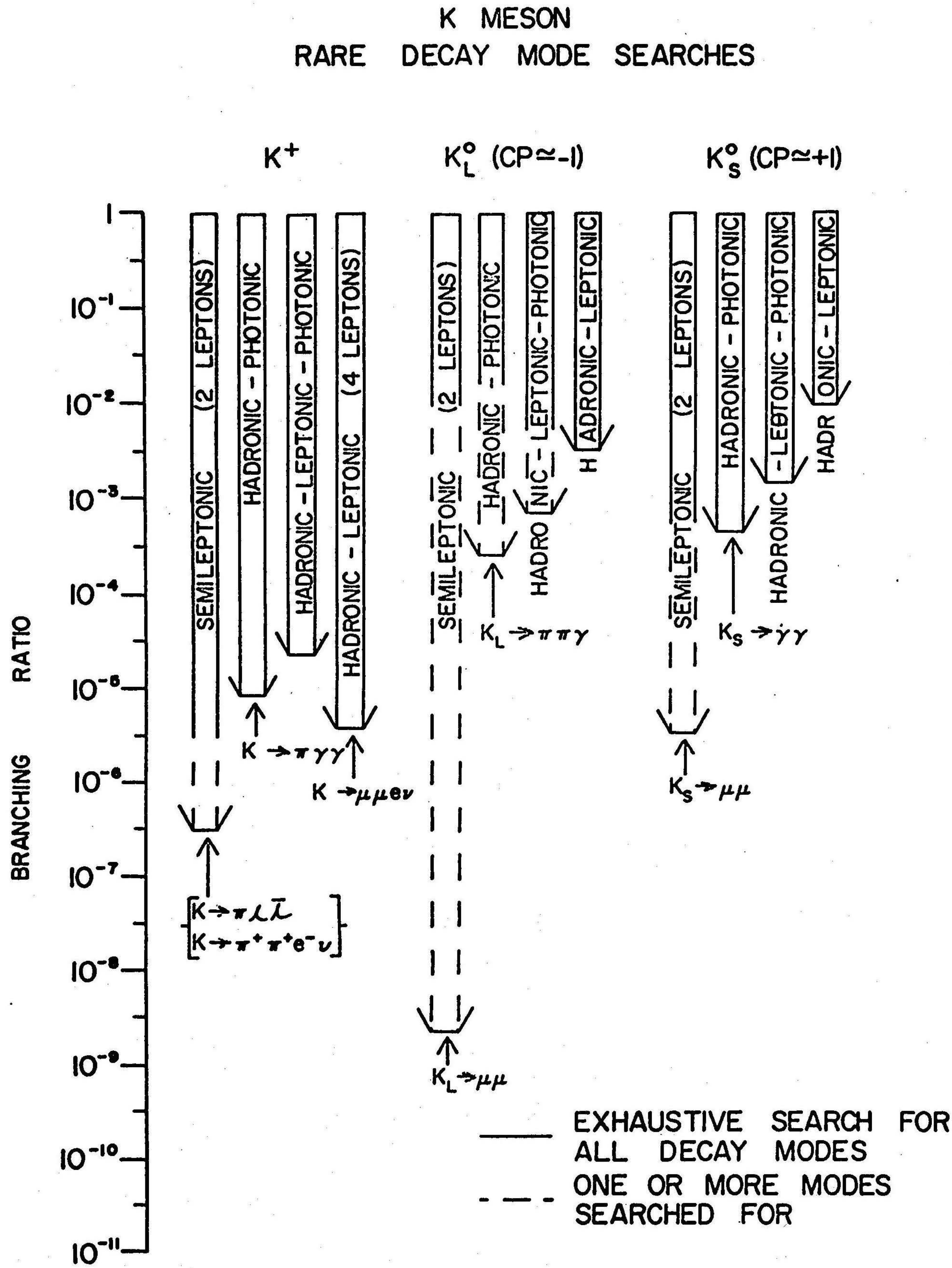

K MESON
RARE DECAY MODE SEARCHES
K^+
K^o_L (CP≃-1)
K^o_S (CP≃+1)
BRANCHING RATIO
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
SEMILEPTONIC (2 LEPTONS)
HADRONIC - PHOTONIC
HADRONIC - LEPTONIC - PHOTONIC
HADRONIC - LEPTONIC (4 LEPTONS)
$K \to \pi \gamma \gamma$
$K \to \mu \mu e \nu$
$K \to \pi \ell \bar{\ell}$
$K \to \pi^+ \pi^+ e^- \nu$
SEMILEPTONIC (2 LEPTONS)
HADRONIC - PHOTONIC
HADRONIC - LEPTONIC - PHOTONIC
HADRONIC - LEPTONIC
$K_L \to \pi \pi \gamma$
$K_L \to \mu \mu$
SEMILEPTONIC (2 LEPTONS)
HADRONIC - PHOTONIC
HADRONIC - LEBTONIC - PHOTONIC
HADRONIC - LEPTONIC
$K_S \to \gamma \gamma$
$K_S \to \mu \mu$
EXHAUSTIVE SEARCH FOR ALL DECAY MODES
ONE OR MORE MODES SEARCHED FOR

Figure 4

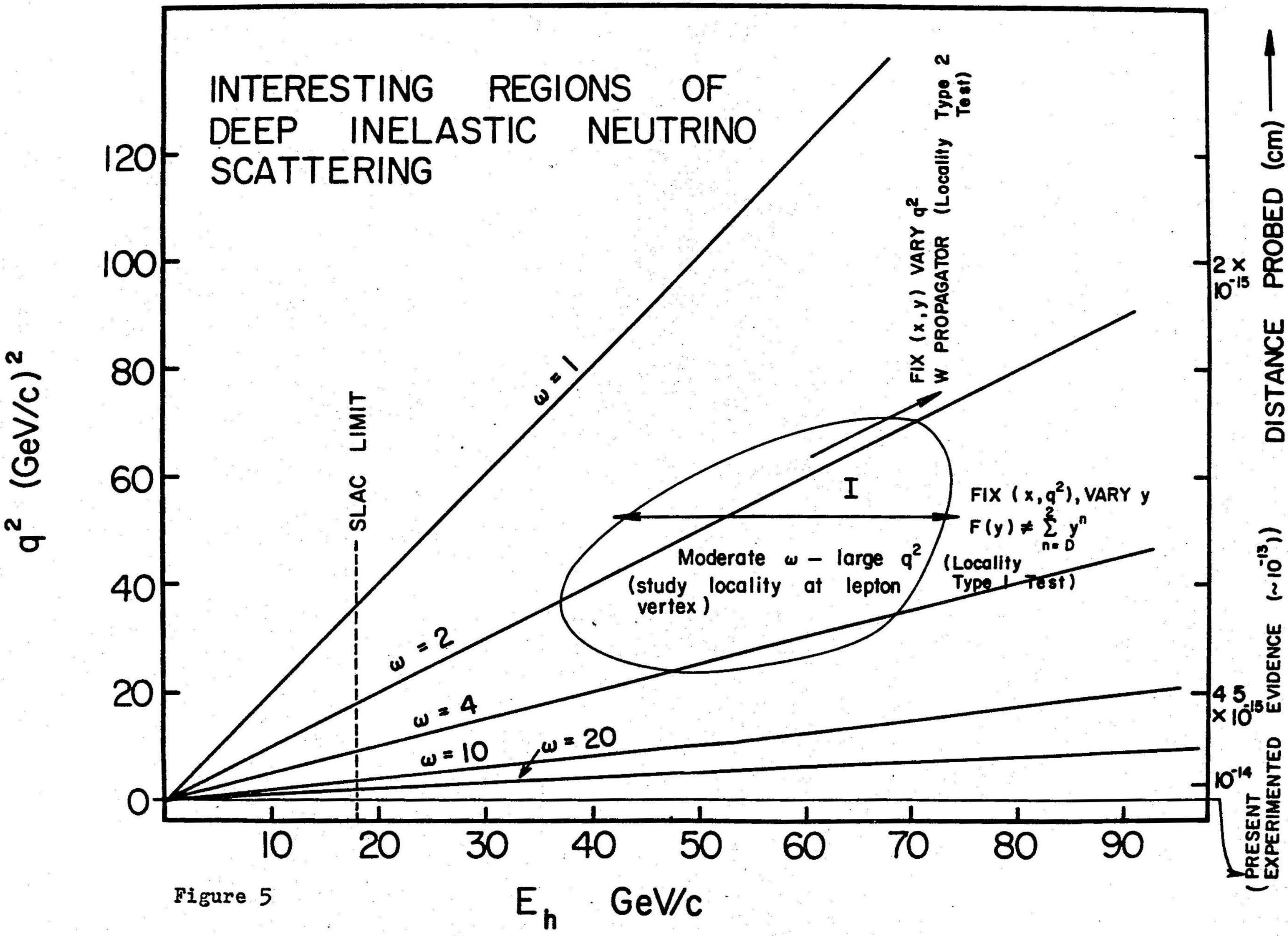

INTERESTING REGIONS OF DEEP INELASTIC NEUTRINO SCATTERING
q² (GeV/c)²
120
100
80
60
40
20
0
10
20
30
40
50
60
70
80
90
E_h GeV/c
SLAC LIMIT
ω = 1
ω = 2
ω = 4
ω = 10
ω = 20
FIX (x,y) VARY q²
W PROPAGATOR (Locality Type 2 Test)
I
FIX (x, q²), VARY y
F(y) ≠ Σ_{n=0}^{2} y^n
(Locality Type I Test)
Moderate ω – large q²
(study locality at lepton vertex)
DISTANCE PROBED (cm)
2 × 10⁻¹⁵
4.5 × 10⁻¹⁵
10⁻¹⁴
(PRESENT EXPERIMENTED EVIDENCE (~10⁻¹³))

Figure 5

HARVARD-PENNSYLVANIA-WISCONSIN NEUTRINO DETECTOR (SCHEMATIC)

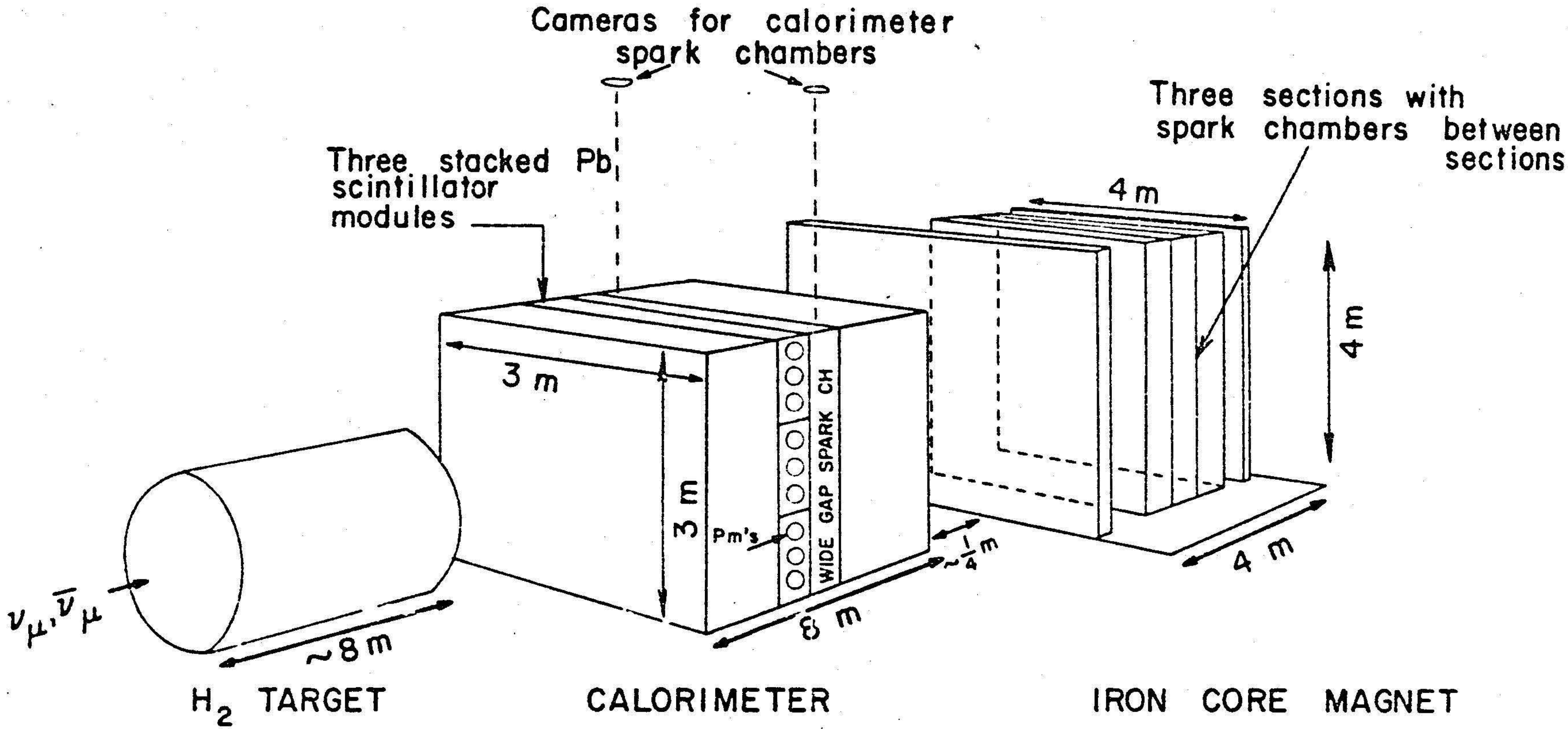


Figure 6